Observations of the transient X-ray pulsar EXO 053109–6609.2 with ASCA, BeppoSAX and XMM-Newton

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Abstract. We report timing and spectral properties of the transient X-ray pulsar EXO 053109-6609.2 using observations carried out with ASCA, BeppoSAX, and XMM-Newton observatories. Pulse period measurements of the source show a monotonic spin-up trend since 1996. The pulse profile is found to have a strong luminosity dependence, a single peaked profile at low luminosity that changes to a double peaked profile at high luminosity. The X-ray spectrum is described by a simple power-law model with photon index in the range of 0.2–0.8. A soft excess over the power-law continuum is also detected from XMM-Newton observation.

INTRODUCTION

High Mass X-ray Binary (HMXB) systems constitute a neutron star or a black hole orbiting around a massive early-type star. In such systems, accretion of matter takes place either via Roche-lobe overflow or from the stellar wind which powers the X-ray emission from the compact object. Nearly about one third of 100 known HMXBs are found in the Small Magellanic Cloud (SMC) and Large Magellanic Cloud (LMC) [1]. These HMXBs are further classified into two subgroups namely supergiant HMXBs and Be X-ray binaries. The companion in a Be X-ray binary system is a Be star with a typical mass of about 10–20 $M_{\odot}$. A non-supergiant early type star with Balmer series emission lines is characterized as a Be star. The emission lines along with the characteristic strong infrared excess provide evidences for the presence of circumstellar material in a disk-like geometry. It is believed that the material forming the disk accelerates radially at distances larger than those probed by the optical emission lines [2]. The orbital periods of the Be X-ray binaries are in the range of about 15 days to years.

The transient Be/X-ray binary EXO 053109-6609.2 was discovered during the EXOSAT observations of LMC X-4 in 1983 [3]. Subsequent observations with the SL2 XRT on the Space Shuttle Challenger revealed hard X-ray emission in the source [4]. ROSAT PSPC observations of EXO 053109-6609.2 led to the discovery of coherent pulsations with a barycentric pulse period of 13.67 s with a rate of change of period as $(1.5\pm0.1) \times 10^{-8}$ s s^{-1} [5]. Its intensity variations were studied in detail with ROSAT [6]. Timing analysis of EXO 053109-6609.2 during 1997 March outburst observed with the narrow field instruments of BeppoSAX shows 13.67 s pulsations with a double peaked pulse profile in 0.1–60 keV energy range [7]. The soft X-ray energy spectrum (0.1–2.4 keV) of EXO 053109-6609.2 was first measured by the ROSAT PSPC [6]. The source spectrum in 2–20 keV band, obtained from SL2 XRT experiment, was described by a power law model with photon index of ~ 1 and equivalent hydrogen column density of $\sim 7 \times 10^{22}$ cm^{-2} [4]. The presence of a soft spectral component below 1 keV, over the hard power law is detected from the XMM-Newton observation of the source [8]. The optical counterpart is one of the two close doubles in the error circle of the EXO 053109-6609.2, each component of which could be a Be star associated with the X-ray source [9].

Here in this paper, we describe the temporal and spectral properties of the Be transient X-ray pulsar EXO 053109-6609.2 using archival data from ASCA, BeppoSAX, and XMM-Newton observatories.

OBSERVATION

The observations of the transient X-ray pulsar EXO 053109-6609.2, used for the present study, were carried out with the instruments onboard the ASCA, BeppoSAX, and XMM-Newton observatories. During the ASCA GIS observation of LMC X-4 in 1996 May

24–26, EXO 053109-6609.2 was in the field of view for a useful exposure of 36 ks. The pulsar was bright enough for the temporal and spectral study. It was also present in the field of view of the BeppoSAX instruments during the observations of LMC X-4 in 1997 March 13–15 for useful exposures of 117 ks and 42 ks with MECS and LECS, in 1998 October 20–22 for 82 ks and 31 ks exposures with MECS and LECS and during the observation of the LMC in 2000 January 01–02 for 32 ks and 15 ks exposures with MECS and LECS respectively. It was also in the field of view of the XMM-Newton observation of the LMC field in 2000 June for 55 ks, 61 ks and 62 ks useful exposures with EPIC-PN, MOS1 and MOS2 detectors respectively.

ANALYSIS AND RESULTS

Timing Analysis

Standard procedure was applied to all observations for data selection and extraction of background subtracted light curves and spectra by selecting appropriate source and background regions of suitable radius. Light curves with time resolution of 0.25 s, 50 s, and 0.25 s were extracted from barycenter corrected event files of the ASCA, BeppoSAX, and XMM-Newton observations. Pulse folding and chi-square maximization technique were applied near the expected pulse period of 13.7 s to detect pulsations in the source light curves. The pulse period measurements with ASCA, BeppoSAX and XMM-Newton observations along with the previous two reported values [5, 7] are given in Table-1. Pulse profiles created from the background subtracted light curves in different energy bands, obtained from all but 1997 BeppoSAX observation, are shown in Figure 1. The estimated 2–10 keV source luminosity during above observations are also shown in corresponding panels of Figure 1. The luminosity dependence of the pulse profile such as a single peaked profile at low luminosity and a double peaked profile at high luminosity is evident from the figure.

Using the measured pulse periods with various observatories, an overall spin up trend with $\dot{P}$ = -0.0019 s yr^{-1} (excluding the first observation in Table 1) is observed in EXO 053109–6609.2. The archival observations are not sufficiently long enough to determine the orbital parameters by applying the pulse arrival time delay technique. Though a peak at 183 days and its integer multiples are seen in the power density spectrum of EXO 053109–6609.2, obtained from the RXTE-ASM light curve, the yearly observational effects cannot be ruled out.

TABLE 1. The pulse period measurements of EXO 053109–6609.2

Date of Obs. (MJD)	Observatory –Instrument	Pulse period (s)
48560.16	ROSAT-PSPC	13.67133 ± 0.00005 [5]
50228.12	ASCA - GIS	13.67875 ± 0.00012
50520.00	SAX - MECS	13.67590 ± 0.00008 [7]
51107.64	SAX - MECS	13.670674 ± 0.000026
51600.72	SAX - MECS	13.66884 ± 0.00004
51824.56	XMM-Newton MOS+PN	13.668153 ± 0.000036

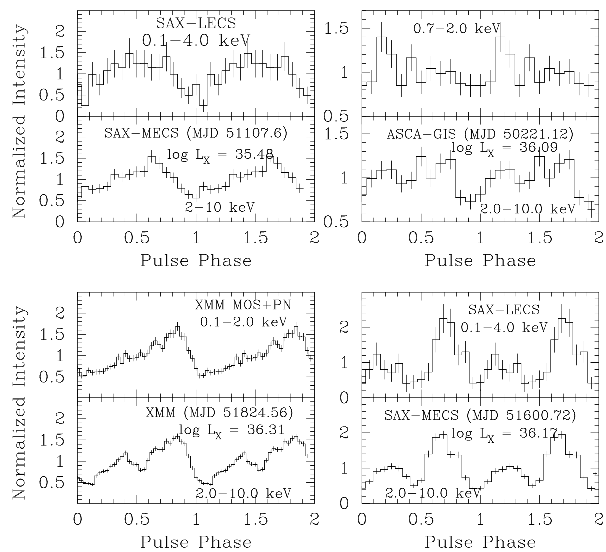

FIGURE 1. Pulse profiles of EXO 053109–6609.2 with the ASCA, BeppoSAX, and XMM-Newton detector arranged in terms of increasing 2–10 keV luminosity.

Spectral Analysis

Spectral fitting to the energy spectra of EXO 053109-6609.2 required significant binning when the source luminosity was too low. The ASCA spectrum fitted with a model consisting of a power-law component and line of sight absorption, gave a photon index of 0.46 and equivalent hydrogen column density of 1.1×10^{21} atoms cm^{-2}. The X-ray luminosity of the pulsar during the ASCA observation is estimated to be 1.2×10^{36} erg s^{-1} (assuming a distance of 55 kpc to the LMC). The spectrum obtained from ASCA-GIS instrument is shown in Figure 2 along with the fitted model and residual.

During the BeppoSAX observations, the source was at a distance of about 17’ away from the center of the field of view of the detectors. Therefore, appropriate effective area for an off-axis angle of 17’ was taken by averaging the corresponding available values for MECS at 14’ and 20’. For spectral fitting, the 1997 September LECS and

TABLE 2. Spectral parameters of EXO 053109-6609.2 during different observations

Parameter	ASCA 1996 GIS2+GIS3	SAX 1997 LECS+MECS23	SAX 1998 LECS+MECS23	SAX 2000 LECS+MECS23	XMM-Newton 2000 PN+MOS1+MOS2
N_H (10^{20} atoms cm^{-2})	11^{90}_{-5}	$5.7^{+3.3}_{-0.0}$	29^{+230}_{-23}	$6.6^{+38}_{-0.9}$	34^{+5}_{-11}
Photon Index (Γ)	$0.46^{+0.63}_{-0.37}$	0.81 ± 0.05	$0.37^{+0.54}_{-0.38}$	0.63 ± 0.17	$0.20^{+0.04}_{-0.08}$
KT_{BB} (keV)	—	—	—	—	0.08 ± 0.01
Iron line flux*	—	3.0 ± 1.2	—	2.8 ± 2.5	0.78 ± 0.36
log L_X (2.0–10.0 keV)†	36.09	36.78	35.48	36.18	36.31
Blackbody flux**	—	—	—	—	1.1 ± 0.4
Reduced χ^2/dof	0.23/9	1.44/79	0.49/20	0.55/46	1.32/463

* 10^{-5} photons cm^{-2} s^{-1}
† 10^{36} erg s^{-1}. Since the absorption column density is not well constrained, the L_X given here is not corrected for absorption
** 10^{-13} erg cm^{-2} s^{-1}

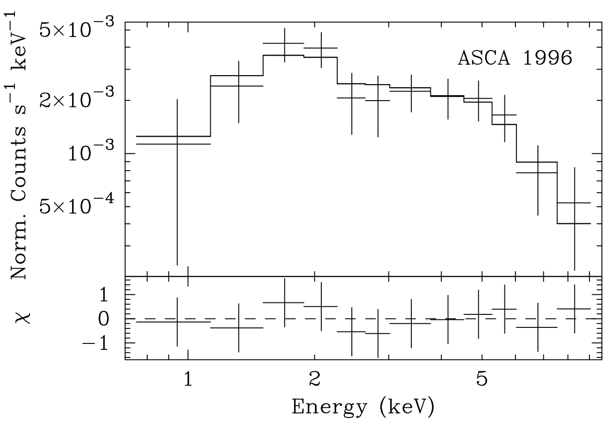

FIGURE 2. Energy spectrum of EXO 053109–6609.2 obtained from ASCA-GIS along with the fitted model and residuals.

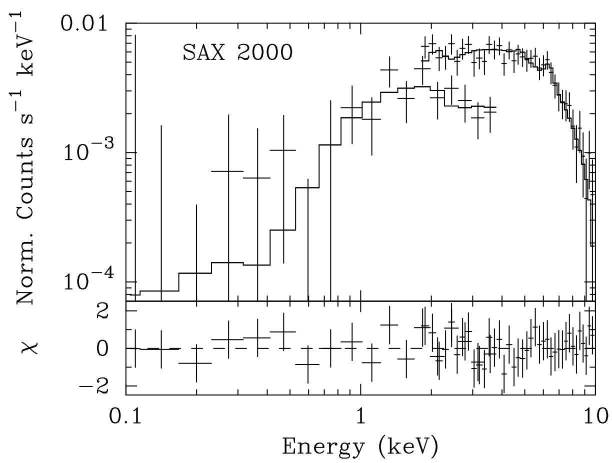

FIGURE 3. Energy spectrum of EXO 053109–6609.2 obtained from BeppoSAX LECS and MECS instruments during 2000 observation along with the fitted model and residuals.

MECS1 response matrices were used. Spectra obtained from all three BeppoSAX observations were fitted with the same model as used for the ASCA spectrum. A line like feature at 6.4 keV in the residuals of the spectra of 1997 and 2000 BeppoSAX observations allowed us to include a narrow Gaussian line at above energy in the spectral model. The equivalent width of iron emission line during above two observations is found to be 130±50 eV and 180±160 eV respectively. The X-ray luminosities in 2–10 keV energy band during 1997, 1998, and 2000 BeppoSAX observations are estimated to be 6.1 × 10^{36}, 3.0 × 10^{35}, and 1.5 × 10^{36} erg s^{-1} respectively. The spectra measured with BeppoSAX LECS and MECS instruments during the 2000 observation are shown in Figure 3 along with the fitted model and residuals.

The source and background spectra of EXO 053109-6609.2 were obtained by selecting suitable circular regions in the images produced from EPIC-PN, MOS1 and MOS2 event data of XMM-Newton observation. Standard procedures were followed to generate response files for corresponding instruments. Simultaneous spectral fitting to the EPIC-PN, MOS1, and MOS2 data with a model consisting of a power-law and line of sight absorption clearly shows the presence of soft excess below 0.8 keV. Addition of a low temperature blackbody component and a Gaussian component at 6.4 keV to the model yielded significant improvement in spectral fitting. The power-law photon index is found to be ∼ 0.2. The equivalent width of the iron emission line is estimated to be 110±45 eV and the blackbody temperature is found to be 0.08 keV. The energy spectra obtained from XMM-Newton observation are shown in Figure 4 along with the spectral components and residuals. The parameters obtained from the spectral fitting to the ASCA, BeppoSAX, and XMM-Newton data are given in Table 2.

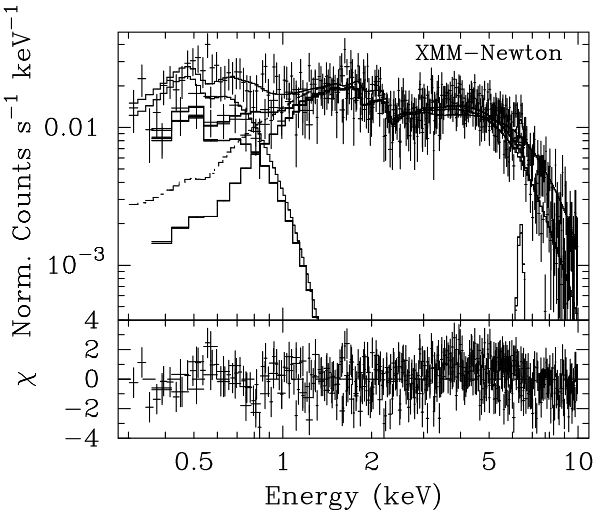

FIGURE 4. Energy spectrum of EXO 053109–6609.2 obtained from EPIC-PN, MOS1, and MOS2 instruments during 2000 XMM-Newton observation along with the spectral components and residuals.

DISCUSSION

The transient Be X-ray pulsars typically show spin-up during their high luminosity states [10]. The pulse period history of the Be transient X-ray pulsar EXO 053109–6609.2 (including the present work) shows that the pulsar was certainly spinning down between the ROSAT PSPC observation in 1991 [5] and the ASCA observation in 1996 (present work). However, all the observations following the one made with ASCA in 1996, show a clear spin up trend in the pulsar though the period derivative keeps varying to some extent. The observed spin-up episodes of the neutron star suggests that the accretion of matter onto the compact object was in progress during the above period.

The shape of the pulse profiles obtained from the ASCA, BeppoSAX, and XMM-Newton observations of EXO 053109–6609.2 are found to be different at different source luminosities. A single peaked and nearly sinusoidal pulse profile at low luminosity (1998 BeppoSAX observation) and a double peaked profile at high luminosity (1997 and 2000 BeppoSAX observations) are clearly seen. During the intermediate luminosities (1996 ASCA and 2000 XMM-Newton observations), the profiles are found to be a mixture of the above two profiles. Different pulse profiles at different luminosities of EXO 053109–6609.2 suggest a change in X-ray beam pattern from a pencil beam at low luminosity to a fan beam in high luminosity state as was seen during the EXOSAT observation of the transient X-ray pulsar EXO 2030+375 [11].

Spectral analysis of the ASCA, BeppoSAX, and XMM-Newton observations of EXO 053109–6609.2 indicates intrinsic variability in the source properties with luminosity. Comparing the power-law photon indices during the above observations, it is found that the power-law component of the source spectrum becomes softer with increasing luminosity. Simultaneous spectral fitting of the EPIC-PN, MOS1 and MOS2 spectra of XMM-Newton observation clearly shows the presence of soft excess over the extended hard power-law component to lower energies, as seen in other accreting X-ray pulsars with relatively low line of sight absorption (SMC X-1 and LMC X-4 [12], and references therein). Different shape of pulse profiles at soft and hard X-ray energy bands, as shown in Figure 1, suggests different origin of the spectral components. A detailed account of the present work is described else where [13].

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